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(54) Super-elastic composite guidewire

(57) This is a composite guidewire for use in a catheter and is used for accessing a targeted site in a lumen system of a patient's body. The guidewire core or guidewire section may be of a stainless steel or a high elasticity metal alloy, preferably a Ni-Ti alloy, also preferably having specified physical parameters. The composite guidewire assembly is especially useful for accessing peripheral or soft tissue targets. Variations include multi-section guidewire assemblies having (at least) super-elastic distal portions and super-elastic braided reinforcements along the mid or distal sections. A variation of the inventive guidewire includes the coating of the wire with a tie layer and then with a one or more lubricious polymers to enhance its suitability for use within catheters and with the interior of vascular lumens.

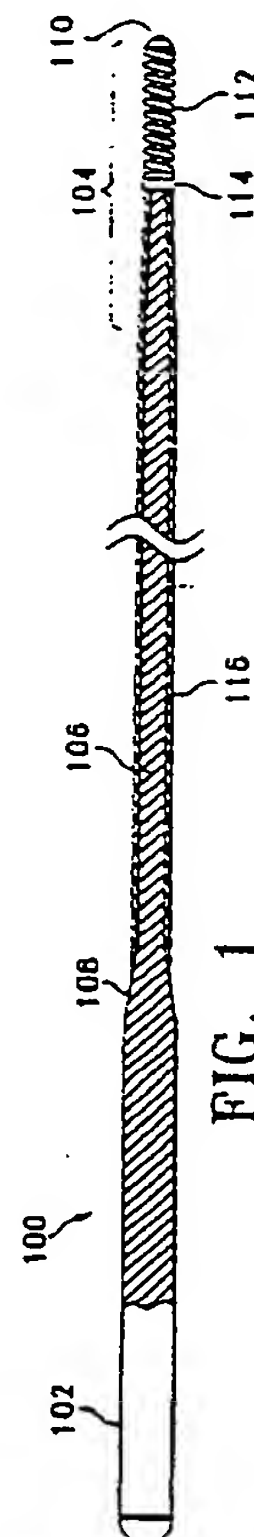


FIG. 1

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Description

This invention is a surgical device. It is a composite guidewire for use in a catheter and is used for accessing a targeted site in a lumen system of a patient's body. The guidewire core or guidewire section may be of a stainless steel or a high elasticity metal alloy, preferably a Ni-Ti alloy, also preferably having specified physical parameters. The composite guidewire assembly is especially useful for accessing peripheral or soft tissue targets. Variations of the invention include multi-section guidewire assemblies having (at least) super-elastic distal portions and super-elastic braided reinforcements along the mid or distal sections. A variation of the inventive guidewire includes the coating of the wire with a tie layer and then with a one or more lubricious polymers to enhance its suitability for use within catheters and with the interior of vascular lumen.

Catheters are used increasingly as a means for delivering diagnostic and therapeutic agents to internal sites within the human body that can be accessed through the various of the body's lumen systems, particularly through the vasculature. A catheter guidewire is used for guiding the catheter through the bends, loops, and branches forming the blood vessels within the body. One method of using a guidewire to direct the catheter through the torturous paths of these systems of lumen involves the use of a torqueable guidewire which is directed as a unit from a body access point such as the femoral artery to the tissue region containing the target site. The guidewire is typically bent at its distal end, and may be guided by alternately rotating and advancing the guidewire along the small vessel pathway to the desired target. Typically the guidewire and the catheter are advanced by alternately moving the guidewire along a distance in the vessel pathway, holding the guidewire in place, and then advancing the catheter along the axis of the guidewire until it reaches the portion of the guidewire already advanced farther into the human body.

The difficulty in accessing remote body regions, the body's periphery or the soft tissues within the body such as the brain and the liver, are apparent. The catheter and its attendant guidewire must be both flexible, to allow the combination to follow the complicated path through the tissue, and yet stiff enough to allow the distal end of the catheter to be manipulated by the physician from the external access site. It is common that the catheter is as long as a meter or more.

The catheter guidewires used in guiding a catheter through the human vasculature have a number of variable flexibility constructions. For instance, U.S. Patent Nos 3,789,841; 4,545,390; and 4,619,274 show guidewires in which the distal end section of the wire is tapered along its length to allow great flexibility in that remote region of the guidewire. This is so, since the distal region is where the sharpest turns are encountered. The tapered section of the wire is often enclosed in a wire coil, typically a platinum coil, to increase the column strength of the tapered wire section without significant loss of flexibility in that region and also to increase the radial capacity of the guidewire to allow fine manipulation of the guidewire through the vasculature.

Another effective guidewire design is found in U.S. Patent No. 5,095,915 which shows a guidewire having at least two sections. The distal portion is encased in an elongated polymer sleeve having axially spaced grooves to allow increased bending flexibility of the sleeve.

Others have suggested the use of guidewires made of various super-elastic alloys in an attempt to achieve some of the noted functional desires.

U.S. Patent 4,925,445, to Sakamoto et al., suggests the use of a two-portion guidewire having a body portion relatively high in rigidity and a distal end portion which is comparatively flexible. At least one portion of the body and the distal end portions is formed of super-elastic metallic materials. Although a number of materials are suggested, including Ni-Ti alloys of 49 to 58% (atm) nickel, the patent expresses a strong preference for Ni-Ti alloys in which the transformation between austenite and martensite is complete at a temperature of 100C or below. The reason given is that "for the guidewire to be useable in the human body, it must be in the range of 100 to 200C due to anesthesia at a low body temperature. The temperature of the human body is typically about 37C.

Another document disclosing a guidewire using a metal alloy having the same composition as a Ni-Ti super-elastic alloy is WO91/15152 (to Sahatjian et al. and owned by Boston Scientific Corp.). That disclosure suggests a guidewire made of the precursor to the Ni-Ti elastic alloy. Super-elastic alloys of this type are typically made by drawing an ingot of the precursor alloy while simultaneously heating it. In the unstressed state at room temperature, such super-elastic materials occur in the austenite crystalline phase and, upon application of stress, exhibit stress-induced austenite-martensite (SIM) crystalline transformations which produce nonlinear elastic behavior. The guidewires described in that published application, on the other hand, are said not to undergo heating during the drawing process. The wires are cold-drawn and great pain is taken to assure that the alloy is maintained well below 3000F during each of the stages of its manufacture. This temperature control is maintained during the step of grinding the guidewire to form various of its tapered sections.

U.S. Patent 4,665,906 suggests the use of stress-induced martensite (SIM) alloys as constituents in a variety of different medical devices. Such devices are said to include catheters and cannulas.

U.S. Patent 4,969,890 to Sugita et al., suggests the production of a catheter having a main body fitted with a shape memory alloy member, and having a liquid injection means to supply a warming liquid to allow the shape memory alloy

member to recover its original shape upon being warmed by the fluid.

U.S. Patent 4,984,581, to Stice, suggests a guidewire having a core of a shape memory alloy, the guidewire using the two-way memory properties of the alloy to provide both tip-deflecting and rotational movement to the guidewire in response to a controlled thermal stimulus. The controlled thermal stimulus in this instance is provided through application of an RF alternating current. The alloy selected is one that has a transition temperature between 360C and 450C. The temperature 360C is chosen because of the temperature of the human body; 450C is chosen because operating at higher temperatures could be destructive to body tissue, particularly some body proteins.

U.S. Patent 4,991,602 to Amplatz et al., suggests a flexible guidewire made up of a shape memory alloy such as the nickel-titanium alloy known as nitinol. The guidewire is one having a single diameter throughout its midcourse, is tapered toward each end, and has a bead or ball at each of those ends. The bead or ball is selected to allow ease of movement through the catheter into the vasculature. The guidewire is symmetrical so that a physician cannot make a wrong choice in determining which end of the guidewire to insert into the catheter. The patent suggests that wound wire coils at the guidewire tip are undesirable. The patent further suggests the use of a polymeric coating (PTFE) and an anticoagulant. The patent does not suggest that any particular type of shape memory alloy or particular chemical or physical variations of these alloys are in any manner advantageous.

Another catheter guidewire using Ni-Ti alloys is described in U.S. Patent No. 5,069,226, to Yamauchi, et al. Yamauchi et al describes a catheter guidewire using a Ni-Ti alloy which additionally contains some iron, but is typically heat-treated at a temperature of about 4000 to 5000C so as to provide an end section which exhibits pseudo-elasticity at a temperature of about 370C and plasticity at a temperature below about 800C. A variation is that only the end portion is plastic at the temperatures below 800C.

U.S. Patent No. 5,171,383, to Sagae, et al., shows a guidewire produced from a super-elastic alloy which is then subjected to a heat treatment such that the flexibility is sequentially increased from its proximal portion to its distal end portions. A thermoplastic coating or coil spring may be placed on the distal portion of the wire material. Generally speaking, the proximal end portion of the guidewire maintains a comparatively high rigidity and the most distal end portion is very flexible. The proximal end section is said in the claims to have a yield stress of approximately five to seven kg/mm² and an intermediate portion of the guidewire is shown in the claims to have a yield stress of approximately 11 to 12 kg/mm².

Published European Patent Application 0,515,201-A1 also discloses a guidewire produced at least in part of a super-elastic alloy. The publication describes a guidewire in which the most distal portion can be bent or curved into a desired shape by a physician immediately prior to use in a surgical procedure. Proximal of the guide tip, the guidewire is of a super-elastic alloy. Although nickel-titanium alloys are said to be most desirable of the class shown in that disclosure, no particular physical description of those alloys is disclosed to be any more desirable than another.

Published European Patent Application 0,519,604-A2 similarly discloses a guidewire which may be produced from a super-elastic material such as nitinol. The guidewire core is coated with a plastic jacket, a portion of which may be hydrophilic and a portion of which is not.

Examples of Ni-Ti alloys are disclosed in U.S. Patent Nos. 3,174,851; 3,351,463; and 3,753,700.

None of these disclosures suggest the guidewire composition or configuration described below.

This invention is a guidewire, preferably a guidewire suitable for introduction into the vasculature of the brain. At least a distal portion of the guidewire may be of a super-elastic alloy which preferably is a Ni-Ti alloy having specific physical characteristics, e.g., a stress-strain plateau at about 75 ± 10 ksi and another at 25 ± 7.5 ksi (each measured at 3% strain) when the stress-strain relationship is measured to a strain of 6%.

A highly desirable variation of the inventive guidewire comprises a long wire having a proximal section, an intermediate section, and a distal section. The guidewire further may have an eccentricity ratio of 1 ± 10^4 . The distal end section is typically the most flexible of the sections and is at least about three centimeters long. Desirably, the flexible distal end section is partially tapered and is covered by a coil assembly which is connected to the distal end of the guidewire at its distal tip. The coil assembly may be attached to the distal tip by soldering, perhaps after plating or coating the distal end section with a malleable or solderable metal, such as gold.

The guidewire, whether of a super-elastic metal or not, may be coated with a polymer or other material to enhance its ability to traverse the lumen of the catheter. A lubricious polymer may be placed directly upon the core wire or upon a "tie" layer. The tie layer may be a shrink-wrap tubing or a plasma deposition or may be a dip, spray, or fusion spray coating of an appropriate material. The tie layer may also be radio opaque.

The guidewire of this invention may be of a composite in which a distal portion of the core is a super-elastic alloy of the type described below and the more proximal section or sections are of another material or configuration, e.g., stainless steel wire or rod, stainless steel hypotube, super-elastic alloy tubing, carbon fiber tubing, etc.

The guidewire of this invention may be of a composite in which a distal portion of the core is a stainless steel or super-elastic alloy and is ground or tapered but is jacketed with a thin coil or braid of a super-elastic alloy ribbon. This provides the guidewire assembly with high flexibility in the distal section due to the tapering and high column strength due to the presence of the super-elastic braid.

Ideally there will be one or more radiopaque markers placed upon the guidewire, e.g., at its distal tip and potentially along the length of the intermediate section. These markers may be used both to enhance the guidewire's radiopacity and its ability to transmit torque from the proximal end to the distal end while maintaining a desired flexibility.

This invention also includes a catheter apparatus made up of the guidewire core and a thin-walled catheter designed to be advanced along the guidewire through the vasculature for positioning at a desired site.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a schematic side view (not to scale) of the major components of the inventive guidewire.

Figure 2 is a partial cutaway, side view of composite guidewire according to this invention having a distal portion of a highly elastic alloy.

Figure 3 is a partial cutaway side view of one embodiment of the distal tip of the Figure 1 device.

Figure 4 is a partial cutaway side view of a second embodiment of the distal tip of the Figure 1 device.

Figure 5A is a partial cutaway side view of a third embodiment of the distal tip of the Figure 1 device.

Figure 5B is a partial cutaway top view of the embodiment shown in Figure 5A.

Figures 6A and 6B show midsection variations, in fragmentary cross-section, of the invention guidewire.

Figure 7 is a partial side view of a guidewire having a braided reinforcement distally.

Figure 8 is a partial side view of a midsection joint in the inventive guidewire.

Figure 9 shows a typical stress-strain diagram for a Ni-Ti alloy displaying objective criteria for selection of alloys for the inventive guidewire.

Figure 10 is a partial cross-section of a guidewire section.

Figure 11 is a graph showing friction on a guidewire test, the guidewire being made according to this invention.

Figure 1 shows an enlarged side view of a guidewire made according to the invention. The guidewire (100) is made up of the wire core formed of a flexible torqueable wire filament material, of the alloys described below, and has a total length typically between about 50 and 300 centimeters. The proximal section (102) preferably has a uniform diameter (along its length) of about 0.010 to 0.025 inches, preferably 0.010 to 0.018 inches. The relatively more flexible distal section (104) extends for 3 to 30 centimeters or more of the distal end of the guidewire (100). There may be a middle section (106) having a diameter intermediate between the diameter of the two portions of the wire adjoining the middle section. The middle section (106) may be continuously tapered, may have a number of tapered sections or sections of differing diameters, or may be of a uniform diameter along its length. If middle section (106) is of a generally uniform diameter, the guidewire core will neck down as is seen at (108). The distal section (104) of the guidewire (100) typically has an end cap (110), a fine wire coil (112), and a solder joint (114). The fine wire coil (112) may be radiopaque and made from materials including but not limited to platinum and its alloys. The end cap (110) may be radiopaque to allow knowledge of the position of the coil (112) during the process of inserting the catheter and traversal of the guidewire through the vasculature. All or part of the guidewire proximal section (102) and middle section (106) and distal section (104) may be coated with a thin layer (116) of polymeric material to improve its lubricity without adversely affecting the flexibility or shapeability of the guidewire. This invention includes portions or sections of the guidewire described above having the noted polymeric tie layer described below and a slippery, e.g., a hydrophilic polymeric coating thereon.

Figure 2 shows a variation of the inventive guidewire which is a composite, e.g., a distal portion of the guidewire core is produced of the specified alloy and the composite is of another material or configuration. In particular, the composite guidewire (140) is made up of a proximal section (142) that is a section of small diameter tubing of, e.g., an appropriate stainless steel or a high performance polymer such as a polyimide or a high elasticity alloy such as those discussed elsewhere herein. Tubular composites such as super-elastic alloy ribbon tubular braids having polymeric coverings and perhaps polymeric interiors are also desirable. The tubular proximal section (142) is attached by soldering or by gluing or by other joining method suitable for the materials involved at the joint (144) to a distal section (146) that extends to the distal end of the composite guidewire assembly (140). The proximal section (142) may instead be a solid rod of a material such as stainless steel or a fibrous carbon composite. The distal tip (148) of the catheter assembly (140) may be of the same configuration as those otherwise described herein. The catheter assembly may be coated (150) with polymeric material, as desired.

Figure 3 shows a partial cutaway of one embodiment of the distal section (104) and the distal end of the intermediate section (106). The metallic guidewire core is shown partially coated with polymer (116) and a malleable metal coating (118) on the tapered portion of the distal tip. The malleable metal may be selected from suitable radiopaque materials such as gold or other easily solderable materials such as silver, platinum, palladium, rhodium, and alloys of the above. The tip also includes a radiopaque coil (112) which is bounded on its proximal end by a solder joint (114) and is joined with the end of the guidewire at (110). The radiopaque coil (112) may be made of known suitable materials such as platinum, palladium, rhodium, silver, gold, and their alloys. Preferred is an alloy containing platinum and a small amount of tungsten. The proximal and distal ends of coil (112) may be secured to the core wire by soldering.

Figure 4 shows a partial cutaway of another embodiment of the distal section (104) of the inventive guidewire. In

this embodiment, the metal guidewire core has a proximal tapered portion (120), a distal tapered section (122) with a solder joint (114) separating the two sections, and a constant diameter tip (124). The distal tip (124) may have constant diameter typically between about 0.002 and 0.005 inches, preferably about 0.003 inches. The distal tip (124) is preferably between about 1 and 5 cm in length, preferably about 2 cm but the portion of constant diameter extends for at least about 25% of the distance between the solder joint (128) and the solder joint (114). This constant diameter section marginally stiffens the distal tip assembly for enhanced control. The entire distal section (104) desirably is between about 20 and 50 cm, preferably about 25 cm in length. The maximum diameter of the proximal tapered portion (120) of the guidewire core typically is between about 0.005 and 0.020 inches, preferably about 0.010 inches. The distal tapered portion (122) and distal tip (124) are again shown with a malleable metal coating (118) such that the distal tapered portion (122) and distal tip (124) stay bent upon forming by the physician. In this embodiment, the fine wire coil (112) is bounded on its proximal end by a solder joint (114) and on its distal end by an end cap (110). The end cap (110) is connected to the guidewire by means of a metallic ribbon (126). The ribbon (126) may be made of stainless steel, platinum, palladium, rhodium, silver, gold, tungsten, and their alloys or other materials which are plastic and that are easily soldered. The ribbon (126) is soldered to the fine wire coil (112) and to the distal tip (124) of the distal section (104) of the guidewire at a solder joint (128) such that the end cap (110) is secured against the fine wire coil (112).

Figures 5A and 5B show yet another inventive embodiment of the distal section (104) of the guidewire (100). Figure 5A shows a side view, partial cutaway of the inventive guidewire. The fine wire coil (112) may be bounded by a polymer adhesive (136) that joins the coil (112) to the core wire and an end cap (110) and further secured to the guidewire core by a solder joint (128). In this embodiment, the distal section (104) of the guidewire again comprises a tapered portion (120) that is proximal to the polymer adhesive (136) and a tapered portion (122) that is distal to the polymer adhesive (136). The distal section (104) also comprises a smaller diameter portion (130) or "neck" that may be surrounded by optional inner coil (132). The inner coil (132) may be made of a suitable metallic material preferably that is easy to solder and preferably radiopaque. It is preferably platinum or stainless steel. One way to produce neck (130) is to flatten the distal portion of the guidewire (134) distal to the neck so that the resulting spade (134) is no longer of circular cross-section but rather is of rectangular shape. This may be more easily visualized in Figure 5B since that Figure shows a cutaway top view of the guidewire shown in Figure 5A. As in above-described embodiments, the end cap (110) is secured to the guidewire by a metallic ribbon (126). The solder joint (128) secures the guidewire core to the inner helical coil (132) which secures the end cap (110) via the ribbon (126) and further secures the outer fine wire coil (112). This configuration is especially valuable for use with guidewire materials which are not easily solderable. The solder joint need not adhere to the guidewire and yet the inner coil (132), ribbon (126); and outer fine wire coil (112) all are maintained as a single integral unit and have no chance of slipping proximally or distally on the guidewire assembly.

Although the embodiment described with reference to Figures 5A and 5B speaks generally of a guidewire made of a high elasticity alloy, materials for the guidewire and the ribbon such as stainless steel, platinum, palladium, rhodium and the like are suitable with that embodiment.

Figures 6A and 6B show partial fragmentary cross-sections of portions of the distal section (170) and the midsection (172) of a variation of the inventive catheter assembly. In the variations shown in Figures 6A and 6B, the core is ground to a smaller diameter to achieve a higher degree of flexibility in those regions. To provide additional column strength and torqueability, a flat wound ribbon (176) (in Figure 6A) or coil (178) (in Figure 6B) is placed on the core. In addition, since many of the super-elastic alloys making up core (174) are not particularly radiopaque, it is often desirable to use radiopaque materials for the ribbon (176) or coil (178) so to permit the physician to observe the position of the guidewire assembly with greater ease. Indeed, it is not uncommon for the ribbons (176) or coils (178) to extend (in conjunction with the coils (112)) to extend 25-35 cm. from the distal tip of the catheter assembly. Again, it is not uncommon for the distal coil (112) to be itself up to 10 cm. or so in length. Finally, it is desirable to use a smaller diameter wire in the more proximal coil (178) than the distal coil (112) to provide a radiopaque view and enhanced column strength to the guidewire belt with lower overall mass.

Alternatively, the ribbon may be of a super-elastic alloy as described elsewhere herein. A super-elastic alloy ribbon is used to provide enhanced column strength at a reduced weight (as compared to the more radiopaque materials). When the ribbon is a super-elastic alloy, it desirably is of a size between 0.0005" and 0.002" (thickness) and 0.002" and 0.012" (width). For ease of fabrication, the ribbon may be 0.00075" to 0.001" in thickness and 0.003" to 0.005" in width.

In addition, we have found it desirable to coat all or part of the guidewire core (as will be discussed in more detail below) with a lubricious coating material such as polyfluorocarbons or with hydrophilic polymers. As is discussed below, when using hydrophilic polymers as the coating material, it is often desirable to use a tie layer on the guidewire core. The composition of such tie layers will be also discussed below. However, in the variation shown in Figures 6A and 6B, the combination of tie layer and hydrophilic polymer (180) is shown as being placed over the midsection stiffeners (176) and (178).

Figure 7 shows a variation of the invention in which the filamentary core (175) has been ground to a taper in its more distal regions. In this aspect, the core is much like other variations which have been discussed above. The core

(175) in this variation may be of a stainless steel or of one of the high elasticity alloys noted elsewhere herein. The core (175) is then at least partially jacketed with a tubular metallic braid (177) which preferably is bonded to the core (175), by adhesives or solder or by welding, either at intervals along the core (175) or continuously from one end of the braid to the other. Although the braid (177) most desired is shown in Figure 7 and has a single size of ribbon, the braid need not be so limited; multiple sizes of ribbon may be used as desired. The major limitations are simply the size, e.g., diameter, of the overall braid as finally constructed and the desired added stiffness to be added to the guidewire.

The braids typically useful in this invention comprise an even number of ribbons: one half of the ribbons wound one way, i.e., clockwise, and the remainder are wound the other way. A typical braid will be of eight to 16 ribbons. The braid may have a single pitch, an angle of a constituent ribbon measured against the axis of the braid, or it may have a pitch which varies along the axis of the braid. The braid may be wound over a mandrel of a size similar to the guidewire core and gently heat-treated on that mandrel at temperature of 6500 to 7500F for a portion of an hour to preserve the shape of the braid and to prevent its unwinding during subsequent installation on the core wire. The braid may also be wound directly onto the core if so desired.

The braid (177) is usually rough to the touch if not covered or further processed. Procedures such as rolling, sanding, or grinding may be used to smooth the surface of the braid if so desired. Removal of any produced particulates is, of course, necessary. Whether the outer surface of the braid (177) is smoothed or not, it is quite desirable to place an outer layer of a lubricious polymer on the exterior of the braiding. The variation shown in Figure 7 utilizes the tie layer (179) discussed elsewhere herein and has a thin layer of a hydrophilic polymeric layer placed on the exterior of the tie layer (179). The hydrophilic polymeric layer is not depicted on the drawing because the layer is typically too thin to see. The tie layer (179) and its associated hydrophilic polymeric layer may be (but need not be) of the same composition as a layer (181) on the more proximal section.

Figure 8 is a partial side view of a midsection joint in the inventive guidewire. On many variations of the inventive guidewire, various sections of the core are joined by tapered sections such as seen at (190). This means that the guidewire core is significantly stiffer at the proximal end of the tapered joint (190). We have found that it is sometimes desirable to place grooves (192) in that proximal end to lower the overall stiffness of the guidewire at that junction and yet retain the columnar strength.

GUIDEWIRE CORE

This guidewire is typically used in a catheter which is made up of an elongate tubular member having proximal and distal ends. The catheter is (again) about 50 to 300 centimeters in length, typically between about 100 and 200 centimeters in length. Often, the catheter tubular member has a relatively stiff proximal section which extends along a major portion of the catheter length and one or more relatively flexible distal sections which provide greater ability of the catheter to track the guidewire through sharp bends and turns encountered as the catheter is advanced through the tortuous paths found in the vasculature. The construction of a suitable catheter assembly having differential flexibility along its length is described in U.S. Patent No. 4,739,768.

We have found that certain alloys, particularly Ni-Ti alloys, retain their super-elastic properties during traversal through the vasculature and yet are sufficiently pliable that they provide the physician using the guidewire with enhanced "feel" or feedback and yet do not "whip" during use. That is to say, as a guidewire is turned it stores energy during as a twist and releases it precipitously as it "whips" to quickly recover the stored stress. The preferred alloys do not incur significant unrecovered strain during use. We have also found that if the eccentricity of the wire, i.e., the deviation of the cross-section of the guidewire from "roundness" (particularly in the middle section) is maintained at a very low value, the guidewire is much easier to steer or direct through the vasculature. The material used in the guidewires of this invention are of shape memory alloys which exhibit super-elastic/pseudo-elastic shape recovery characteristics. These alloys are known. See, for instance, U.S. Patent Nos. 3,174,851 and 3,351,463 as well as 3,753,700; however, the '700 patent describes a less desirable material because of the higher modulus of the material due to an increased iron content. These metals are characterized by their ability to be transformed from an austenitic crystal structure to a stress-induced martensitic (SIM) structure at certain temperatures, and return elastically to the austenitic structure when the stress is removed. These alternating crystalline structures provide the alloy with its super-elastic properties. One such well-known alloy, nitinol, is a nickel-titanium alloy. It is readily commercially available and undergoes the austenite-SIM-austenite transformation at a variety of temperature ranges between -200C and 300C.

These alloys are especially suitable because of their capacity to elastically recover almost completely to the initial configuration once the stress is removed. Typically there is little plastic deformation, even at relatively high strains. This allows the guidewire to undertake substantial bends as it passes through the body's vasculature, and yet return to its original shape once the bend has been traversed without retaining any hint of a kink or a bend. However, the tips shown are often sufficiently plastic that the initial tip formation is retained. Nevertheless, compared to similar stainless steel guidewires, less force need be exerted against the interior walls of the vessels to deform the guidewire of the invention along the desired path through the blood vessel thereby decreasing trauma to the interior of the blood vessel

and reducing friction against the coaxial catheter.

A guidewire, during its passage through the vasculature to its target site, may undertake numerous bends and loops. The desirability of enhancing the ease with which a guidewire may be twisted to allow the bent distal tip to enter a desired branch of the vasculature cannot be overstated. We have found that a major factor in enhancing such ease of use, that is, in enhancing the controllability of the guidewires is by controlling the eccentricity of the cross-section of the middle portion of the guidewire. We have found that by maintaining the middle portion of the guidewire (106 in Figure 1) to an eccentricity ratio of 1 ± 10^{-4} , the guidewire is significantly more controllable than those which fall outside this ratio. By "eccentricity", we mean that at any point along the guidewire the ratio of the largest diameter at that cross-section to the smallest diameter of the wire at that cross-section.

To achieve these results of high strength and enhanced control even while allowing feedback to the attending physician during use, we have found that the following physical parameters of the alloy are important. In a stress-strain test as shown on a stress-strain diagram such as that found in Figure 9, the stress found at the midpoint of the upper plateau (UP) (measured, e.g. at about 3% strain when the test end point is about 6% strain) should be in the range of 75 ksi (thousand pounds per square inch) ± 10 ksi and, preferably, in the range of 75 ksi ± 5 ksi. Additionally, this material should exhibit a lower plateau (LP) of 25 ± 7.5 ksi, preferably 20 ± 2.5 ksi, measured at the midpoint of the lower plateau. The material preferably has no more than about 0.25% residual strain (RS) (when stressed to 6% strain and allowed to return) and preferably no more than about 0.15% residual strain.

The preferred material is nominally 50.6% $\pm 0.2\%$ Ni and the remainder Ti. The alloy should contain no more than about 500 parts per million of any of O, C, or N. Typically such commercially available materials will be sequentially mixed, cast, formed, and separately co-worked to 30-40%, annealed and stretched.

By way of further explanation, Figure 9 shows a stylized stress-strain diagram showing the various parameters noted above and their measurement on that diagram. As stress is initially applied to a sample of the material, the strain is at first proportional (a) until the phase change from austenite to martensite begins at (b). At the upper plateau (UP), the energy introduced with the applied stress is stored during the formation of the quasi-stable martensite phase or stress-induced-martensite (SIM). Upon substantial completion of the phase change, the stress-strain relationship again approaches a proportional relationship at (c). The stress is no longer applied when the strain reaches 6%. The measured value (UP) is found at the midpoint between zero and 6% strain, i.e., at 3% strain. If another terminal condition of strain is chosen, e.g., 7%, the measured values of (UP) and (LP) would be found at 3.5%.

Materials having high UP values produce guidewires which are quite strong and allow exceptional torque transmission but cause a compromise in the resulting "straightness" of the guidewire. We have found that guidewires having high UP values in conjunction with high LP values are not straight. These guidewires are difficult to use because of their tendency to "whip" as they are turned. Again, that is to say, as a guidewire is turned it stores energy during a twist and releases it quickly. The difficulty of using such a whipping guidewire should be apparent. Materials having UP values as noted above are suitable as guidewires.

Furthermore, materials having values of LP which are high, again, are not straight. Lowering the value of LP compromises the ability of the guidewire to transmit torque but improves the ease with which a straight guidewire may be produced. Lowering the LP value too far, however, results in a guidewire which, although round, has poor tactile response. It feels somewhat "vague" and "soupy" during its use. The LP values provided for above allow excellent torque transmission, straightness, and the valuable tactile response.

The values of residual strain discussed above define a materials which do not kink or otherwise retain a "set" or configuration after stress during use as a guidewire.

EXAMPLE

In each instance, the following procedure was used in producing the data displayed in the table which follows: commercial Ni-Ti alloy wires having a nominal composition of 50.6% Ni and the remainder Ti, and diameters of 0.13", 0.16", or 0.18" were stressed at room temperature. In each instance, values for transition temperature, PS, UP, and LP were measured. Additionally, several of the noted wires were introduced into a U-shaped Tygon tube and spun to allow qualitative evaluation of the roundness and tactile response of the wires. Comments on that response are also found in the following table.